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LARGE $p_\perp$ EXCLUSIVE PROCESSES: RECENT DEVELOPMENTS

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Abstract

Recent improvements of the hard scattering picture for exclusive reactions, namely the inclusion of both Sudakov corrections and the intrinsic transverse momentum dependence of the hadronic wave function, are reviewed. On account of these improvements the perturbative contribution to the pion's form factor can be calculated in a theoretically self-consistent way for momentum transfers as low about 2 GeV. This is achieved at the expense of a substantial suppression of the perturbative contribution in the few GeV region. Eventual higher twist contributions are also discussed.

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1. The hard scattering picture

There is general agreement that perturbative QCD in the framework of the hard-scattering picture (HSP) [1] is the correct description of form factors and perhaps other exclusive reactions at asymptotically large momentum transfer. In the HSP a form factor or a scattering amplitude is expressed by a convolution of distribution amplitudes (DA) with hard scattering amplitudes calculated in collinear approximation within perturbative QCD. The universal, process independent DAs, which represent hadronic wave functions integrated over transverse momenta ($k_\perp$), are controlled by long distance physics in contrast to the hard scattering amplitudes which are governed by short distance physics. The DAs cannot be calculated by perturbative means, we have to rely on models. In principle lattice gauge theory offers a possibility to calculate the DAs but with the present-day computers a sufficient accuracy can not be achieved, only a few moments of the pion and proton DAs have been obtained [2].
As an example of an exclusive reaction let us consider the electromagnetic form factor of the pion. To lowest order pertubative QCD the hard scattering amplitude T_H is to be calculated from the two one-gluon exchange diagrams. Working out the diagrams one finds

$$T_H(x_1, y_1, Q, \vec{k}_\perp, \vec{l}_\perp) = \frac{16\pi\, \alpha_s(\mu)\, C_F}{x_1 y_1 Q^2 + (\vec{k}_\perp + \vec{l}_\perp)^2}, \tag{1.1}$$

where $Q (\geq 0)$ is the momentum transfer from the initial to the final state pion. x_1 (y_1) is the longitudinal momentum fraction carried by the quark and $\vec{k}_\perp$ ($\vec{l}_\perp$) its transverse momentum with respect to the initial (final) state pion. The momentum of the antiquark is characterized by $x_2 = 1 - x_1$ ($y_2 = 1 - y_1$) and $-\vec{k}_\perp$ ($-\vec{l}_\perp$). C_F ($= 4/3$) is the colour factor and α_s is the usual strong coupling constant to be evaluated at a renormalization scale μ. The expression (1.1) is an approximation in so far as only the most important $\vec{k}_\perp$- and $\vec{l}_\perp$-dependences have been kept. Denoting the wave function of the pion's valence Fock state by Ψ_0, the form factor is given by

$$F_\pi(Q^2) = \int \frac{dx_1\, d^2k_\perp}{16\pi^3} \int \frac{dy_1\, d^2l_\perp}{16\pi^3}\, \Psi_0^*(y_1, \vec{l}_\perp)\, T_H(x_1, y_1, Q, \vec{k}_\perp, \vec{l}_\perp)\, \Psi_0(x_1, \vec{k}_\perp). \tag{1.2}$$

Strictly speaking Ψ_0 represents only the soft part of the pion wave function, i.e. the full wave function with the perturbative tail removed from it [1]. Contributions from higher Fock states are neglected in (1.2) since, at large momentum transfer, they are suppressed by inverse powers of Q^2.
At large Q one may neglect the $k_\perp$- and $l_\perp$-dependence in the gluon propagator as well; T_H can then be pulled out of the transverse momentum integrals, and these integrations apply only to the wave functions. Defining the DA as

$$\frac{f_\pi}{2\sqrt{6}}\, \phi(x_1, \mu) = \int \frac{d^2k_\perp}{16\pi^3}\, \Psi_0(x_1, \vec{k}_\perp), \tag{1.3}$$

one arrives at the celebrated hard-scattering formula for the pion's form factor

$$F_\pi{}^{HSP}(Q^2) = \frac{f_\pi{}^2}{24} \int dx_1\, dy_1\, \phi^*(y_1, \mu)\, T_H(x_1, y_1, Q, \mu)\, \phi(x_1, \mu), \tag{1.4}$$

which is valid for $Q \to \infty$. The DA is defined such that

$$\int_0^1 dx_1\, \phi(x_1, \mu) = 1. \tag{1.5}$$

An immediate consequence of the definitions (1.3) and (1.5) is that the constraint from the $\pi \to \mu\nu$ decay [3] is automatically satisfied:

$$\frac{f_\pi}{2\sqrt{6}} = \int \frac{dx_1\, d^2k_\perp}{16\pi^3}\, \Psi_0(x_1, \vec{k}_\perp), \tag{1.6}$$

where f_π ($= 133\,\mathrm{MeV}$) is the usual π decay constant. The integral in (1.3) has to be cut off at a scale of order Q, which leads to a very mild dependence of the DA on the renormalization scale (QCD evolution). An appropriate choice of the renormalization scale is $\mu = \sqrt{x_1 y_1} Q$. This avoids large logs from higher order pertubation theory at the expense, however, of a singular behaviour of α_s in the end-point regions, $x_i, y_i \to 0$, $i = 1, 2$. It is argued that radiative corrections (Sudakov factors) will suppress that singularity and, therefore, in practical applications of the HSP one may handle that difficulty by cutting off α_s at a certain value, which is typically chosen in the range of 0.5 to 0.7. That crude receipe is unsatisfactory although the Sudakov argument itself is correct as will be discussed in the next section.

Similarly to the pion's form factor other exclusive quantities can be calculated at large transverse momentum. The HSP has two characteristic properties, the quark counting rules and the helicity sum rule. The first property says that the fixed angle cross-section behaves at large Mandelstam s (and large transverse momentum) as

$$\frac{d\sigma}{dt} = f(\theta) s^{2-n} \qquad \text{(modulo logs)} \tag{1.7}$$

where n is the minimum number of external particles in the hard scattering amplitude. The power laws also apply to form factors: a baryon form factor behaves as $1/Q^4$, a meson form factor as $1/Q^2$ at large Q. These power laws are in surprisingly good agreement with experimental data. Even at momentum transfers as low as 2 GeV the data seem to respect the counting rules.

The second characteristic property of the HSP is the conservation of hadronic helicity. For a two-body process, $AB \to CD$ the helicity sum rule reads

$$\lambda_A + \lambda_B = \lambda_C + \lambda_D. \tag{1.8}$$

It appears as a consequence of utilizing the collinear approximation and of dealing with (almost) massless quarks which conserve their helicities when interacting with gluons. The collinear approximation implies that the relative orbital angular momentum between the constituents has a zero component in the direction of the parent hadron. Hence the constituents helicities sum up to the helicity of their parent hadron. Experiments, e.g. the polarization in elastic proton-proton scattering [4] or the recent measurement ot the proton's Pauli form factor [5], reveal that the hadronic helicity is not conserved; the ratio of hadronic helicity flip matrix elements to non-flip ones is about 0.2 - 0.3. That fact can be regarded as a hint at sizeable higher twist contributions in the few GeV region. The physical origin of these higher twist contributions is not yet known. The higher twist nature of the Pauli form factor is clearly visible in Fig. 1: F_2 behaves as $1/Q^6$ at large Q. It is important to realize that the HSP in its present form cannot predict such higher twist terms.

There are many calculations of large $p_\perp$ exclusive reactions within the framework of the HSP: Electromagnetic form factors of mesons and baryons, $N \to N^*$ transition form factors, Compton scattering off nucleons, photoproduction of mesons, two-photon annihilations into pairs of mesons or baryons, decays of heavy mesons such as $\psi \to p\bar{p}$ or $B \to \pi\pi$. No clear picture has been emerged as yet; there are successes and failures. It however seems that one only obtains results of the order of the experimental values if, at least for the proton and the pion, DAs

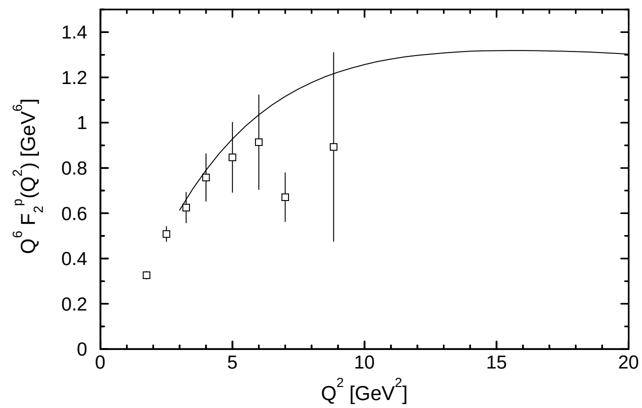

Figure 1: *The Pauli form factor of the proton scaled by Q^6. Data are taken from Ref.* [5]*. The solid line represents the results obtained from the diquark model* [22]*.*

are used which are strongly concentrated in the end-point regions. Such DAs, first proposed by Chernyak and Zhitnitsky (CZ) [6], find a certain justification in QCD sum rules by means of which a few moments of the DAs have been calculated. The CZ moments are subject of considerable controversy: Other QCD sum rule studies provide other values for the moments [7]. Likewise the results obtained from lattice gauge theories do not well agree with the CZ moments [2].

On the other hand, the asymptotic forms of the DAs ($\sim x_1x_2$ for the pion, $\sim x_1x_2x_3$ for the proton), into which any DA evolves for $Q \to \infty$, lead to results which are typically orders of magnitudes too small as compared with data. Consider, as an example, the magnetic form factor of the proton. For the DAs of the CZ type one obtains $Q^4G_M \sim 1\mathrm{GeV}^4$ in agreement with experiment, whereas a vanishing result is found for the asymptotic DA.

Purely hadronic reactions, as for instance elastic proton-proton scattering, have not yet been studied in the frame work of the HSP. The reason for that fact is, on the one hand, the huge number of Feynman diagrams contributing to such reactions and, on the other hand, the occurence of multiple scatterings (pinch singularities [8]), i.e. the possibility that pairs of constituents scatter independently in contrast to the HSP in which all constituents collide within a small region of space-time. A general framework for treating multiple scattering contributions has been developed by Botts and Sterman [9].

2. The Botts-Li-Sterman approach

The applicability of the HSP at experimentally accessible momentum transfers, typically a few GeV, was questioned [7, 10]. It was asserted that in the few GeV region the hard-scattering picture accumulates large contributions from the soft end-point regions, rendering the perturbation calculation inconsistent. This is in particular the case for the end-point concentrated DAs. Another source of theoretical inconsistency is caused by the collinear approximation: The neglect of the transverse momentum dependence of the hard scattering amplitude, see for instance eq. (1.1), is a bad approximation in the end-point regions. How strongly the results, say for the pion's form factor (1.4), are distorted by that approximation depends on the shape of the DAs. Obviously, for DAs of the CZ type, for which the end-point regions get strong

weights, the neglect of the transverse momentum dependence of the hard scattering amplitude entails large errors in the final results. Therefore, that approximation cannot be retained for the DAs of the CZ type. For the asymptotic DA and similar forms the approxiations turns out to be reasonable. For details see Sect. 3.

The statements made by the authors of [7, 10] were challenged by Sterman and collaborators [9, 11, 12]. These authors suggest to retain the transverse momentum dependence of the hard scattering amplitude and to take into account Sudakov corrections, suppressing the dangerous end-point regions even further. In order to include the Sudakov corrections it is advantageous to reexpress eq. (1.2) in terms of the Fourier transform variable $\vec{b}$ in the transverse configuration space

$$F_\pi{}^{pert}(Q^2) = \int_0^1 \frac{dx_1\, dy_1}{(4\pi)^2} \int_{-\infty}^{\infty} d^2b\, \hat{\Psi}_0^*(y_1, \vec{b}, w)\, \hat{T}_H(x_1, y_1, Q, b, t)\, \hat{\Psi}_0(x_1, -\vec{b}, w) \times \exp\left[-S(x_1, y_1, Q, b, t)\right] \quad (2.1)$$

where the Fourier transform of a function $f = f(\vec{k}_\perp)$ is denoted by $\hat{f} = \hat{f}(\vec{b})$. As the renormalization scale Sterman et al. choose the largest mass scale appearing in $\hat{T}_H$:

$$t = \mathrm{Max}(\sqrt{x_1 y_1}\, Q, w = 1/b). \quad (2.2)$$

The factor $\exp[-S]$ in (2.1), termed the Sudakov factor, comprises the radiative corrections. The lengthy expression for the Sudakov exponent S, which includes all leading and next-to-leading logarithms, is given explicitly in [11]. The most important term in it is the double logarithm

$$\frac{2}{3\beta_1} \ln \frac{\xi Q}{\sqrt{2}\Lambda_{QCD}} \ln \frac{\ln(\xi Q/\sqrt{2}\Lambda_{QCD})}{\ln(1/b\Lambda_{QCD})}, \quad (2.3)$$

where ξ is one of the fractions, x_i or y_i, and $\beta_1 = (33 - 2n_f)/12$. For small b, i.e. at small transverse separation of quark and antiquark, there is no suppression from the Sudakov factor. As b increases the Sudakov factor decreases, reaching zero at $b = 1/\Lambda_{QCD}$ (see Fig. 2). For b larger than $1/\Lambda_{QCD}$ the Sudakov factor is set to zero. Owing to that cut-off the singularity of α_s is avoided without introducing a phenomenological parameter (e.g. a gluon mass). For $Q \to \infty$ the Sudakov factor damps any contribution except those from configurations with small quark-antiquark separation. In other words, the hard-scattering contributions dominate the pion's form factor asymptotically.

Li and Sterman have explored the improved hard-scattering formula (2.1) on the basis of customary wave functions, neglecting the QCD evolution and the intrinsic transverse momentum dependence of the wave functions. Their numerical studies have revealed that the modified perturbative approach is self-consistent for $Q > 20\Lambda_{QCD}$ in the sense that less than, say, 50% of the result is generated by soft gluon exchange ($\alpha_s > 0.7$). In the few GeV region the values for F_π as obtained by Li and Sterman are somewhat smaller than those provided by the hard-scattering formula (1.4) and are, perhaps, smaller than the experimental values [13], see Fig. 3.

3. The intrinsic $k_\perp$-dependence of the hadronic wave function

The approach proposed by Sterman and collaborators [9, 11, 12] certainly constitutes an enormous progress in our understanding of exclusive reactions at large momentum transfer. In

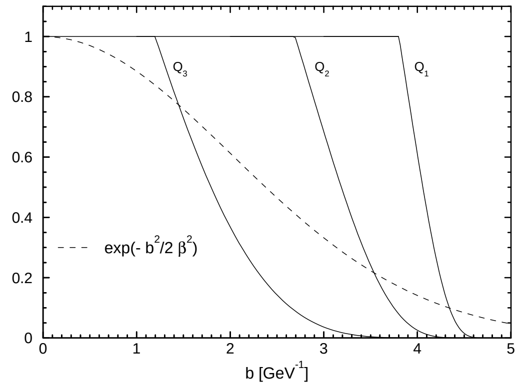

Figure 2: *The Sudakov factor, evaluated at* $x_1 = y_1 = 1/2$*, and the Gaussian* $\exp(-b^2/2\beta^2)$ *(see eq.* (3.4)*) as functions of the transverse separation* b*. The Gaussian is shown for a r.m.s. transverse momentum of* 350 MeV *(dashed line). The Sudakov factor is evaluated at* $Q_1 = 2\,\mathrm{GeV}$*,* $Q_2 = 5\,\mathrm{GeV}$ *and* $Q_3 = 20\,\mathrm{GeV}$ *with* $\Lambda_{QCD} = 200\,\mathrm{MeV}$ *(solid lines).*

any practical application of that approach one has however to allow for an intrinsic transverse momentum dependence of the hadronic wave function [14], although, admittedly, this requires a new phenomenological element in the calculation. Fortunately, for the case of the pion the intrinsic transverse momentum of its valence Fock state wave function is well constrained.
In accordance with (1.3), (1.5) and (1.6), the wave function can be written as

$$\Psi_0(x_1, \vec{k}_\perp) = \frac{f_\pi}{2\sqrt{6}}\,\phi(x_1)\,\Sigma(x_1, \vec{k}_\perp), \tag{3.1}$$

the function Σ being normalized in such a way that

$$\int \frac{d^2k_\perp}{16\pi^3}\,\Sigma(x_1, \vec{k}_\perp) = 1. \tag{3.2}$$

The wave function (3.1) is subject to the following constraints: It is normalized to a number $P_{q\bar{q}} \leq 1$, the probability of the valence quark Fock state; the value of the configuration space wave function at the origin is determined by the the π decay constant (see eq. (1.6)); the process $\pi^0 \to \gamma\gamma$ provides a third relation [3]. Finally, the charge radius of the pion provides a lower limit on the root mean square (r.m.s.) transverse momentum, actually it should be larger than 300 MeV. The $k_\perp$-dependence of the wave function is parametrized as a simple Gaussian

$$\Sigma(x_1, \vec{k}_\perp) = 16\pi^2\beta^2\,g(x_1)\,\exp\left(-g(x_1)\beta^2 k_\perp^2\right), \tag{3.3}$$

$g(x_1)$ being either 1 or $1/x_1x_2$. The latter case goes along with a factor $\exp(-\beta^2 m_q^2/x_1x_2)$ in the DA where m_q is a constituent quark mass (330 MeV). The Gaussian (3.3) is consistent with the required large-$k_\perp$ behaviour of a soft wave function. Several wave functions have been employed in [14]. Here, in the present paper, only the results for the two extreme cases utilized in [14] are quoted. That is, on the one hand, the CZ wave function $\sim x_1x_2(x_1 - x_2)^2$, $g = 1$ [6] which is the example most concentrated in the end-point region and, on the other hand, the modified asymptotic (MAS) wave function $\sim x_1x_2$, $g = 1/x_1x_2$ [3]. The MAS wave function is the example least concentrated in the end-point regions.
The wave functions have one free parameter, the oscillator parameter β, which is fixed by requiring specific values for the r.m.s. transverse momentum. For a value of 350 MeV all the constraints on the pion wave functions are well respected [14]. For a value of 250 MeV for

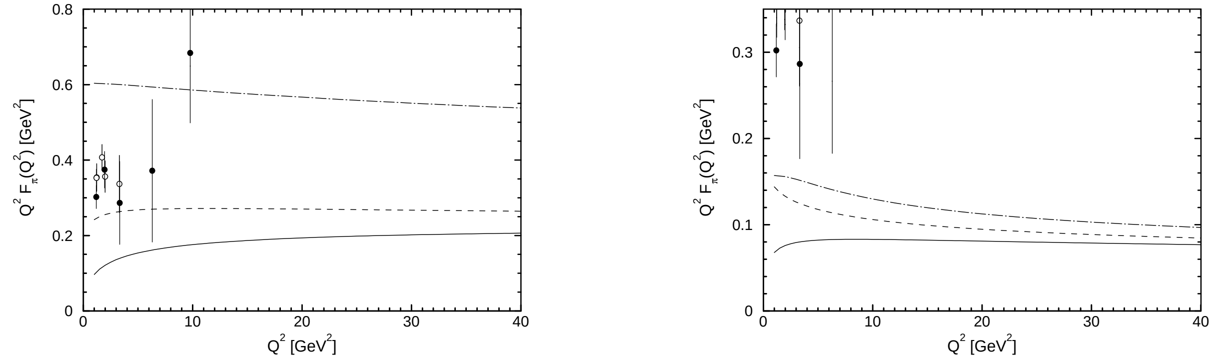

Figure 3: *(Left) The pion's form factor as a function of* Q^2 *evaluated with the CZ wave function and* $\Lambda_{QCD} = 200\,\mathrm{MeV}$. *The dash-dotted line is obtained from the hard-scattering formula with* α_s *cut off at 0.5 and the dashed line from* (2.1) *ignoring the intrinsic* $k_\perp$*-dependence. The solid line represents the complete result obtained from* (2.1) *taking into account both the Sudakov factor and the intrinsic* $k_\perp$*-dependence (*$\langle k_\perp^2\rangle^{1/2} = 350\,\mathrm{MeV}$*). Data are taken from* [13] *(∘ 1976, • 1978).*
(Right)As left figure but using the MAS wave function. Note the modified scale of the abscissa.

instance the constraint from $\pi^0 \to \gamma\gamma$ decay is badly violated and the radius of the pion is too large [14].
The Fourier transform of the $k_\perp$-dependent part of the wave function reads

$$\hat{\Sigma}(x_1, \vec{b}) = 4\pi \, \exp\left(-\frac{b^2}{4g(x_1)\beta^2}\right). \tag{3.4}$$

Li and Sterman [11] assume that the dominant b-dependence of the integrand in eq. (2.1) arises from the Sudakov factor and that the Gaussian in $\hat{\Sigma}$ can consequently be replaced by 1. In order to examine that assumption, the Gaussian is compared with the Sudakov factor in Fig. 2. Obviously the intrinsic $k_\perp$-dependence of the wave function cannot be ignored. For momentum transfers of the order of a few GeV the wave function damps the integrand in (2.1) more than the Sudakov factor. Only at very large values of Q does the Sudakov factor take over.
Numerical evaluations of the pion's form factor through (2.1), using the various wave functions mentioned above, confirm the observations made in Fig. 2. The intrinsic transverse momentum dependence of the wave function provides additional suppression to that due to the Sudakov factor (see Fig. 3). The suppression is particular strong for the end-point concentrated wave functions. These observations confirm the statements made at the end of Sect. 1: The so-called success of the DAs of the CZ-type is only fictitious; for finite values of Q the HSP formula (1.4) does not represent a reasonable approximation to (1.2) for such DAs. The neglect of the $k_\perp$-dependence in the hard scattering amplitude is unjustified in that case.
Thus one can conclude that the intrinsic $k_\perp$-dependence of the wave function has to be taken into account for a reliable quantitative estimate of the perturbative QCD contribution to the pion's form factor. One has to be aware that this introduces a new phenomenological element into the calculation. That disadvantage is, at least partially, compensated by the fact that the inclusion of the intrinsic $k_\perp$-dependence renders the perturbative contribution even more self-consistent than the Sudakov suppression already does. Applying the criterion of self-consistency as suggested by Li and Sterman [11] (see above), we can conclude that perturbative QCD begins to be self-consistent for Q at about $2\,\mathrm{GeV}$ (for $\langle k_\perp^2\rangle^{1/2} = 350\,\mathrm{MeV}$). The exact value of Q at

which self-consistency sets in depends on the wave function. It is larger for the end-point concentrated wave functions than for the asymptotic or MAS DAs. However, the perturbative contribution (2.1), although self-consistent, is presumably too small with respect to the data. A definite conclusion on that point is unfortunately not yet possible since the data may suffer from large systematic errors [15].

An analogous investigation of the proton's form factor, for which precise data is at our disposal, may allow a decisive conclusion on the agreement between the perturbative contribution and experiment. Such an analysis has unfortunately not yet been carried out.

Suppose the contributions from the improved HSP are indeed too small for the pion's and the proton's form factor. Hence other contributions must play an important role in the few GeV region. Obviously, for a perturbative calculation one may suspect higher order contributions to be responsible for the discrepancy between theory and experiment. In analogy to the Drell-Yan process such contributions may be condensed in a K-factor multiplying the lowest order result for the form factor

$$K = 1 + \frac{\alpha_S(\mu)}{\pi} B(Q,\mu) + \mathcal{O}(\alpha_S). \tag{3.5}$$

Calculations of the one-loop corrections [16, 17] reveal that the magnitude of the K-factor strongly depends on the renormalization scale. It is in general large except the renormalization scale is chosen like $\mu = \sqrt{x_1 y_1}Q$ (see Sect. 1). With such a choice and the use of the asymptotic DA, K is about 1.3 in the few GeV region. For DAs broader than the asymptotic one, i.e. for such with a stronger weight of the end-point regions, B seems to become negative. Note that at least part of the K-factor is included in the Sudakov factor. With regard to the new developments discussed above it is perhaps advisable to reanalyse the α_S^2 corrections.

Missing soft contributions offer another explanation of the eventual discrepancy between theory and experiment. As the $k_\perp$-effects discussed above such contributions are of higher twist type and do not respect the quark counting rules. Dominance of such contributions in the case of the pion's form factor and perhaps in other exclusive quantities would leave unexplained the apparent agreement between the counting rules and experiment (see Sect. 1).

There are several possible sources for such soft contributions:

i) Genuine soft contributions like VMD contributions or contributions from the overlap of the soft parts of the hadronic wave functions may fill in the eventual gap between the pertubative contribution and experiment. Allowing for sufficiently many vector mesons the VMD models are flexible enough to account for the form factor data even at large Q (see for instance Ref. [18]). The overlap contribution can be estimated with the aid of the famous Drell-Yan formula [19] (note that the HSP represents the contribution from the overlap of the perturbative tails of the hadronic wave functions). Using the wave functions (3.1), (3.3) one finds for the pion case

$$F_\pi{}^{soft}(Q^2) = \frac{\pi^2}{3} f_\pi{}^2 \beta^2 \int dx_1\, g(x_1)\, \phi^2(x_1)\, \exp\left(-g(x_1)\, \beta^2\, x_2{}^2\, Q^2/2\right). \tag{3.6}$$

The integral is dominated by the region near $x_1 = 1$, other regions are strongly damped by the Gaussian. For example, taking $g = 1$, the effective region is $1 - \sqrt{2}/Q\beta \geq x_1 \geq 1$. Hence F_π^{soft} sensitively reacts to the behaviour of the DA for $x_1 \to 1$. Evaluations of (3.6) reveal that the MAS wave function provides a soft contribution of the right magnitude to fill in the gap between the perturbative contribution (2.1) and the experimental data (see Fig. 4). As required by the consistency of the entire picture, F_π^{soft} decreases faster with increasing Q than the perturbative contribution. The exponential $\exp(-\beta^2 m_q^2/x_1 x_2)$ multiplying the asymptotic DA turns out to be quite important since it is effective in the end-point regions: It reduces the size of F_π^{soft} substantially and leads to an exponentially damped decrease for $Q \to \infty$. F_π^{soft} becomes equal to the perturbative contribution at $Q \simeq 5\,\mathrm{GeV}$. The soft contributions are also

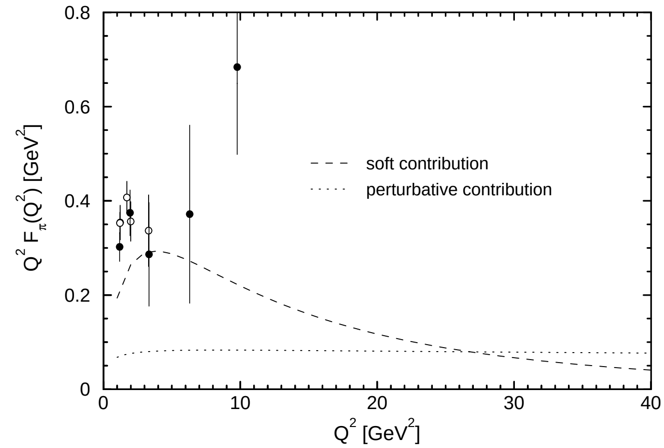

Figure 4: *Comparison of the soft (dashed line) and the perturbative (dotted line) contributions to the pion's form factor evaluated for the MAS wave function.*

subject to Sudakov corrections. For the MAS wave function these corrections amount to a few per cent. The CZ wave function provides a very large soft contribution because of its strong concentration in the end-point regions. The size of that contribution is extremely sensitive to details such as the QCD evolution. Therefore, this wave function appears to be unrealistic. Soft contributions of the type (3.6) have also been discussed in [10]. Our results for F_π^{soft} are similar in trend, but smaller in size than those presented in [10]. Strong soft contributions to form factors have also been obtained with QCD sum rules [7].

I would like to emphasize that in the HSP as well as in the Drell-Yan formula the soft hadronic wave function is input. It is an unknown function since it cannot be calculated with a sufficient degree of accuracy from QCD at present. Thus, to some extend, a study of a form factor serves rather as a determination of the wave function than as a prediction of the form factor. A predictive power is only achieved if that wave function can be used to calculate other reactions. In the HSP this is possible: For instance, the DA of the proton is fixed in a study of the form factor and subsequently used in order to predict, say, Compton scattering off protons. In general soft models do not allow the study of other reactions without introducing new unknown parameters and/or functions.

ii) There may be orbital angular momentum components in the hadronic wave function other than zero. For instance, the valence Fock state component of the pion may be expressed by

$$\int \frac{dx_1\, d^2k_\perp}{16\pi^3} \frac{1}{\sqrt{2}}\, (\not p + m)\, \left[\Psi^0(x_1, \vec{k}_\perp) + \not k_\perp \Psi^1(x_1, \vec{k}_\perp)\right] \gamma_5, \tag{3.7}$$

where p denotes the pion's momentum and m its mass. A new phenomenological function, Ψ^1 appears in (3.7) which is certainly a disadvantage but may lead to a better quantitative description of the pion's form factor data. Treating quark and antiquark as free particles, the expansion of their spinors around the direction of their parent pion provides a model function for Ψ^1:

$$\Psi^1 = \Psi^0/x_1x_2. \tag{3.8}$$

$L \neq 0$ components may also appear in other hadronic wave functions. They have the appealing consequence that the helicity sum rule is violated for finite values of Q. This may offer the possibility to calculate the Pauli form factor of the proton.

iii) Contributions from higher Fock states are another source of higher twist contributions. Also

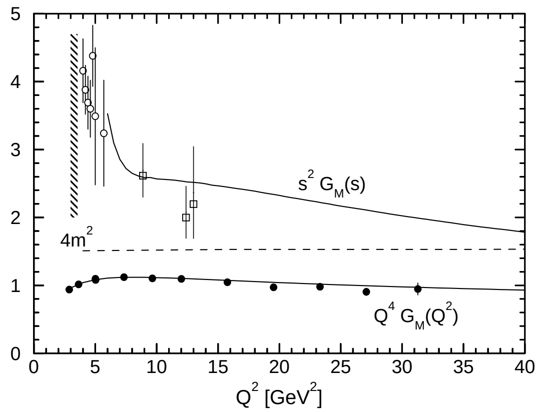

Figure 5: *The magnetic form factor of the proton in the time-like and space-like (at $Q^2 = -s$) regions. The time-like data are taken from Ref.* [26], *the space-like data from Ref.* [27]. *The solid lines represent the predictions of the diquark model* [21], *the dashed line is Hyer's prediction* [24].

in this case new phenomenological functions have to be introduced.
iv) For baryons one may also think of quark-quark correlations in the wave functions which also constitute higher twist effects. In a series of papers [20, 21, 22] the idea has been put forward that such correlations can effectively be described as quasi-elementary diquarks. A systematic study of all exclusive photon-proton reactions has been carried out in that diquark model, which is a variant of the unmodified HSP: form factors in the space-like and in the time-like regions, virtual and real Compton scattering, two-photon-annihilations into proton-antiproton as well as photoproduction of mesons. A fair description of all the data has been achieved utilizing in all cases the same proton DA (as well as the same values for the few other parameters specifying the diquarks). The diquark model allows to calculate helicity flip amplitudes and consequently to predict for instance the Pauli form factor of the proton. The results for it, shown in Fig. 1, are in agreement with the data. Results for the magnetic form factor in both the time-like and the space-like regions are shown in Fig. 5. Although the proton DA used in these studies is not strongly concentrated in the end-point regions, it is rather of the MAS type, it still remains to be seen how much Sudakov factors and the intrinsic $k_\perp$-dependence of the proton wave function will change the results.

4. Other applications of the modified HSP

Up to now only a few applications of the modified HSP have been published. More work is urgently needed. According to what I said above a systematic study of all the photon-proton reactions in that framework would be extremely important. From a comparison between predictions and the many accurate data we have at our disposal for that class of reactions one may be able to draw definite conclusions about the magnitude of the higher twist contributions and perhaps to elucidate their nature.
Li [12] has calculated the magnetic form factor of the proton or rather the Dirac form factor F_1 in the space-like region. Fair agreement with the data is obtained if a DA of the CZ type is used. The calculation turns out to be self-consistent for $Q \geq 30\Lambda_{QCD}$. With a value of

200 MeV for Λ_{QCD} the region of self-consistency is beyond the measured region. The intrinsic $k_\perp$-dependence of the wave function has not been taken into account by Li. I expect, on the basis of our experience with the pion's form factor, that the region of self-consistency is extendend down to much smaller values of Q if the intrinsic $k_\perp$-dependence is taken into account but this will likely be achieved at the expense of a suppression of the perturbative contribution.
Coriano et al. [23] have calculated the academic process Compton scattering off pions in that framework. Again the intrinsic $k_\perp$-dependence of the pion wave function has not been taken into account.
Finally, Hyer [24] has investigated the magnetic form factor of the proton in the time-like region as well as $\gamma\gamma \rightarrow p\bar{p}$. According to Hyer the latter process can only be calculated in a self-consistent way at rather large values of s which prevents a comparison with the new data from CLEO [25]. The predictions from the diquark model, on the other hand, agree very well with the CLEO data [21]. For the time-like form factor of the proton Hyer finds values which are about a factor of 1.5 larger than those obtained by Li [12] for space-like form factor. The reason for Hyer's result is not clear: He has not analytically continued the Sudakov factor and the gluon propagators. Therefore, one would expect from this calculation about the same values for the form factor in both the regions the time-like and space-like ones. Comparing with the data of the Fermilab E760 collaboration [26] (see Fig. 5), Hyer's result is still somewhat too small. Thus, one is tempted to consider the large difference between the time-like and space-like data for the magnetic form factor of the proton as another hint at strong soft contributions in the $5 - 15\,\mathrm{GeV}^2$ region. Note that the diquark model accounts quite well for that difference.

5. Summary

The improved HSP which includes both the Sudakov corrections and the intrinsic $k_\perp$-dependence of the hadronic wave function constitutes an enormous progress in our understanding of exclusive reactions although there are still some theoretical problems left over. At least for the pion's form factor it has been shown that the improved HSP allows to calculate the perturbative contribution to that form factor in a theoretically self-consistent way for momentum transfers as low as about 2 GeV. This is, however, achieved at the expense of a strong suppression of the perturbative contribution as compared to that obtained with the original unmodified HSP. Now the perturbative contribution is likely too small as compared to data. Similar results are to be expected for other exclusive reactions, as for instance the magnetic form factor of the proton. It thus seems that other contributions (higher twists) also play an important role in the few GeV region as already indicated by polarization effects observed in various exclusive reactions and by the recently measured Pauli form factor of the proton. An interesting task for the future is to find out the size of such higher twist contributions and to elucidate their physical nature. Finally, I would like to emphasize that the approximate validity of the quark counting rules, for which the HSP offers an explanation, would remain a mystery if all data for large $p_\perp$ exclusive processes are dominated by soft contributions.
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